Tidal disruption of NEAs - a case of Příbram meteorite

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ABSTRACT

This work studies the dynamical evolution of a possible meteor stream along the orbit of the Příbram meteorite, which originated in the tidal disruption of the putative rubble-pile-like parent body during a close approach to the Earth. We assumed the disruption at the time when the ascending or descending node of the parent orbit was close to the Earth's orbit. In the last 5000 years, the Příbram orbit has crossed the Earth orbit twice. It happened about 4200 years and 3300 years ago. In both cases, we modeled the release of particles from the simplified model of rotating asteroid, and traced their individual orbital evolution to the current date. It takes several hundred years to spread released meteoroids along the entire orbit of the parent body. Even today, the stream would be relatively narrow.

Considering a model parent body with physical parameters of the asteroid Itokawa, the complete disintegration of the object produced 3.8×10^{11} meteoroid particles with diameter $\geqslant 1$ cm. The meteor activity observed from the Earth is revealed and justification of follow-up observation during suggested activity of the shower in the first two weeks of April is discussed.

The Earth's tidal forces would disintegrate a fraction of NEA population into smaller objects. We evaluate the upper limit of mass of disintegrated asteroids within the mean NEA lifetime and the contribution of disrupted matter to the size distribution of the NEA.

Key words: meteorites – meteoroids – asteroids: tidal disruption.

1 INTRODUCTION

The idea of meteoroid streams coming from asteroids was presented in the past (Olivier 1925, Hoffmeister 1937, Halliday, Blackwell & Griffin 1990, Porubčan, Williams & Kornoš 2004, Trigo-Rodríguez et al. 2007, etc.). For instance Halliday, Blackwell & Griffin (1990) analyzed orbits of 89 bolides from the Canadian and American bolide network (MORP and Prairie Network) that might survive the atmospheric flight with a non-zero remaining mass and suggested the existence of streams producing meteorites. The mentioned authors concluded that these streams originated from asteroids. Porubčan, Williams & Kornoš (2004) searched for genetic relations between asteroids and bolide meteoroid streams. The authors investigated the evolution of the orbits and only include as real asteroid-stream pairs those where the evolution was also similar over 5000 years.

The question is what could cause the escape of the matter from the parent asteroids if not collision with another cosmic body? There are several other mechanisms that may cause the disintegration of the asteroidal body: YORP effect spin-up, thermal stress break-up and tidal disruption of

the asteroid during its close fly-by around the planet. Among the terrestrial planets the Earth is the dominant planet that is able to disrupt and distort approaching bodies. Unlike in the case of comets, when the stream of meteoroids is regularly replenished, asteroids can undergo the mentioned events sparsely and streams of meteoroids are rather created by a single event. Therefore, the spatial density of such a stream should be lower and the expected activity hardly distinguished from the sporadic background.

The major motivation for this work was the fall of the Neuschwanstein meteorite on April 6, 2002. The analysis of its heliocentric orbit revealed that the orbit was almost identical to the orbit of Příbram meteorite observed on April 7, 1959 (Spurný, Oberst & Heinlein 2003). Although the two meteorites are of different types (Příbram an ordinary H5 chondrite, Neuschwanstein an enstatite EL6 chondrite) and their cosmic ray exposure times differ (12 and 48 million years, respectively), Spurný, Oberst & Heinlein (2003) proposed an existence of meteoroid stream that might originated in the tidal break-up of an heterogeneous rubble-pile-like asteroid. The evidence of high internal porosity of asteroids, e.g. (253) Mathilde, irregular

shapes, e.g. (1620) Geographos, (216) Kleopatra, (66391) 1999 KW$_4$, detailed surface images of (25134) Itokawa and spin barrier of asteroids with diameters exceeding approx. 200 m imply that a significant fraction of asteroids could have heavily cracked interiors or rubble-pile-like structures. Such conglomerates hold together only by a relatively weak gravity. Surface images of Itokawa also suggested a movement of rubble and dust on the surface in the past (Miyamoto et al. 2007a, Miyamoto et al. 2007b) and further theoretical works (Richardson, Bottke & Love 1998, Scheeres 2007, Rossi, Marzari & Scheeres 2009) present that asteroids may change their shapes or lose mass by the YORP spin-up or tidal break-up. If only surface is resurfaced, some boulders may hide and some emerge, which could explain different cosmic ray exposure times for meteoroids coming from the same parent body as seen in the case of Příbram and Neuschwanstein.

Our previous paper (Kornoš, Tóth & Vereš 2008) showed that the orbital evolution of Příbram and Neuschwanstein exhibits similar behavior at least during the last 5000 years. The Southworth-Hawkins D-criterion for both orbits remains lower than $D_{SH} < 0.07$ and the difference between longitudes of perihelion less than 3°. Moreover, cloned orbits derived within the orbit uncertainties of both meteorites are stable as well. Therefore, the putative stream of meteoroids along the orbit of Příbram could be stable at least for thousands of years, which is consistent with Pauls & Gladman (2005) who derived its decoherence time of about 50 000 years. If there is such a stream, it must have originated relatively recently.

The search for possible members of the Příbram meteor stream brought several suspicious meteors from the IAU meteor orbit database and asteroids from the Minor Planet Center database (Spurný, Oberst & Heinlein 2003, Kornoš, Tóth & Vereš 2008). For instance the asteroid 2002 QG$_{46}$ and meteor 161E1 are relatively near to Příbram orbit, but they do not exhibit orbit similarity as Příbram and Neuschwanstein. Even though Pauls & Gladman (2005) showed that statistically such a close pair could exist as a coincidence. Such conclusion shall not be drawn (Kornoš, Tóth & Vereš 2009) while the count estimates of one meter size NEAs differ more than two order of magnitude.

In this paper, we study the orbital evolution of potential meteoroid stream along the orbit of Příbram. The stream originated in the tidal disruption of the parent body in the past, several thousand years ago. The second and third chapters deal with the origin and particle motion of the meteoroid stream, its orbital evolution and the activity of such a stream today. The fourth chapter deals with the fly-by frequency of the NEAs within the Earth Roche limit. Available Earth impact frequency is adapted. Moreover, it is assumed that the limit rises as a function of the spin rate of the asteroid and the cross-section target plane of the asteroid disruption grows. The fifth chapter evaluates the fraction of NEAs that could be tidally disrupted by the Earth during the median population lifetime in the NEO space, and the amount of disintegrated matter and size-frequency of the altered population is discussed.
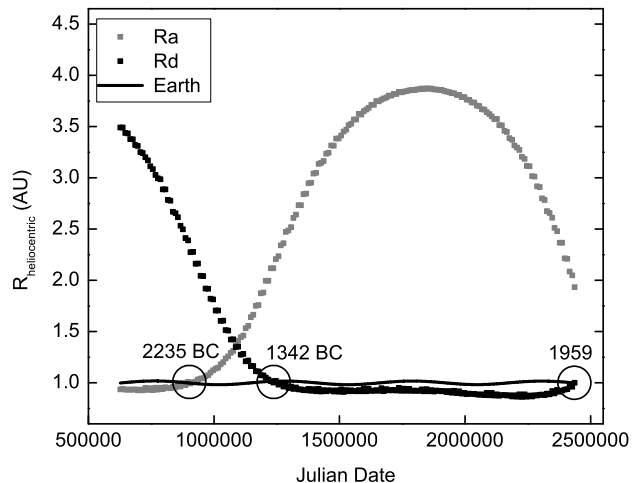

Figure 1. Evolution of heliocentric distance of ascending and descending nodes of Příbram and Neuschwanstein during the last 5000 years.

2   METEOROID STREAM AS A RESULT OF ASTEROID TIDAL BREAK-UP

The complex problem of the asteroid break-up due to the tidal forces has been presented in several papers (Bottke, Richardson & Love 1997, Bottke, Richardson & Love 1998, Richardson, Bottke & Love 1998, Sharma, Jenkins & Burns 2006, Holsapple & Michel 2008). According to the recent results a weak rubble-pile asteroid is deformed during a close fly-by around a planet (Earth) to the shape of the rotational ellipsoid and the matter starts to leave the surface from the ends of the longest axis. Even if the asteroid survives the close encounter, a significant amount of matter leaves the surface in form of regolith, pebbles and boulders.

In the work of Kornoš, Tóth & Vereš (2009), we modeled the release of meteoroid particles from the parent asteroid during its fly-by around the Earth within the Roche limit. The parent body was placed on the orbit of Příbram meteorite. Particles loosed from the surface reached escape velocities around 10 $cm\,s^{-1}$. In the model of hyperbolic motion of the progenitor asteroid around the Earth, modeled particles are only several hundred meters away from the asteroid when the geocentric distance reaches 100 000 km after the perigee passage. The orbital evolution of loose particles only weekly depends on the progenitor's orbit. After hundreds of years particles are distributed along the entire orbit of the parent and even after 1000 years (~ 250 revolutions around the Sun) orbital elements of individual particles are still not much dispersed.

According to the orbital evolution of Příbram and Neuschwanstein, we investigated the heliocentric distance of the ascending and descending nodes (Figure 1). During the last 5000 years, the node has gotten close to the Earth's orbit twice. We assigned the tidal disruption event to these dates. The period when the node got close to the Earth orbit takes tens of years. We selected the middle of the time interval as the exact date of the event. For both dates, we performed simplified tidal disruption of the modeled Itokawa like asteroid as in the previous work (Kornoš, Tóth & Vereš
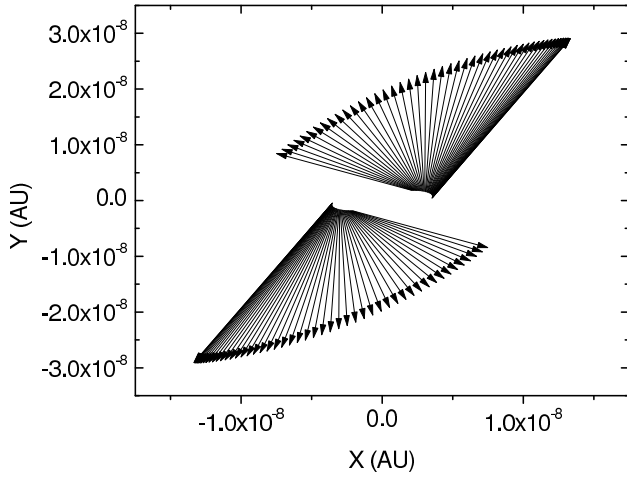
Figure 2. Distribution of position and velocity vectors of particles leaving the surface of the asteroid after its tidal disruption with respect to the center of the mass of the asteroid. The figure depicts the situation in the distance of 100 000 km from the Earth after the perigee and Roche limit passage.

Figure 3. The distribution of particles created by the tidal break-up of the parent asteroid. Modeled particles are spread along the progenitor's orbit within several hundred years.

2009). During each event, 3100 particles were numerically integrated and the orbital evolution was traced. Position and velocity vectors of released particles with respect to the parent asteroid are displayed in Figure 2.

The older event occurred ~ 4200 years ago (JD = 905 120), the more recent event 3300 years ago (JD = 1 231 420). In the study, the multistep Adams-Bashforth-Moulton type up to the 12th order numerical integrator, with a variable step-width, was used. All planets were considered as perturbing bodies and Earth and Moon were treated separately.

3   METEOROID STREAM CHARACTERISTICS

It takes several centuries to redistribute all released particles along the entire orbit. Even today, 3300 years (4200 years, respectively) after the event, particles are orbiting the Sun in a narrow stream along the orbit of the progenitor (Figure 3). The older stream is spread more widely because the node of the orbit crosses the Earth's orbit about 1000 years later after the release. That causes additional perturbation of meteoroid orbits.

The distribution of orbital elements to the current date implies that particles created in both events are on stable orbits (Figure 4). The dispersion in the semimajor axis does not exceed 0.05 AU, 0.04 in the eccentricity, 5° in the inclination for the older event and 2° for the younger event. Argument of perihelion and longitude of ascending node show higher dispersion; however, their sum, the longitude of the perihelion, is within several degrees. The exact elements of Příbram and Neuschwanstein depicted in the Figure 4 are within the intervals of stream orbital elements.

The total number of modeled particles does not provide sufficient sample of meteors crossing the Earth's orbit during the activity period. Therefore, we adopt the analogue of the target plane defined as the plane going through the center of the Earth and perpendicular to the velocity vector of the
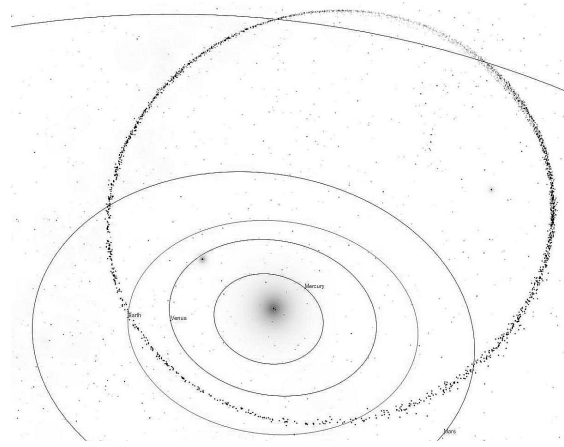
asteroid during its close fly-by. The plain was placed to the position and orientation at the moment of the Příbram meteorite fall in 1959. Target hits by released particles within one of their entire revolutions around the Sun are displayed in Figure 5. Particles released in the older event are spread to a larger area.

From the geometry of the particle motion through the target plain one can estimate that the Earth crosses the stream for approx. 8 days. Figure 6 shows the radiant positions of modeled particles that hit the Earth in 2009. The radiation area of simulated meteors is almost $5° \times 5°$ wide in RA and Dec. The plot also displays the actual positions of Příbram and Neuschwanstein radiants. If the observed meteors from the Příbram stream come from the tidal disruption of the parent asteroids in the event 4200 years ago, the real meteors could have similar radiant distribution during the shower activity as shown in Figure 6. The mean radiant has coordinates $RA = 192.8° \pm 1°$, $Dec = 18.3° \pm 2°$ and the ephemeris of the radians is then derived as:

$$RA = 192.8° + 0.73\,(L_\odot - 17.79°)$$
$$DC = 18.3° + 0.51\,(L_\odot - 17.79°) \tag{1}$$

where $17.79°$ represents the Solar longitude of Příbram fall in 1959 (eq. 2000.0).

To estimate the meteor activity of the prospective meteor stream along the orbit of Příbram, we need to know the size distribution of released particles and their total number. As we already mentioned above, the model asteroid has the same physical properties as the near Earth asteroid Itokawa. Precise measurements of its mass, density, topography, volume and porosity are known from the in-situ exploration by Japanese probe Hayabusa (Abe et al. 2006b). The analysis of the detail surface images provides data about the pebbles and boulders cumulative size distribution (Saito et al. 2006):

$$N(> D) = BD^{-2.8} \ , \tag{2}$$

where the slope -2.8 was derived for the cumulative size distribution for surface features with diameters in the range from 20 cm to 20 m. Supposing that the same size distribution is valid for the wider interval of sizes between 0,01 m and 30 m, the total mass of the asteroid is given as:
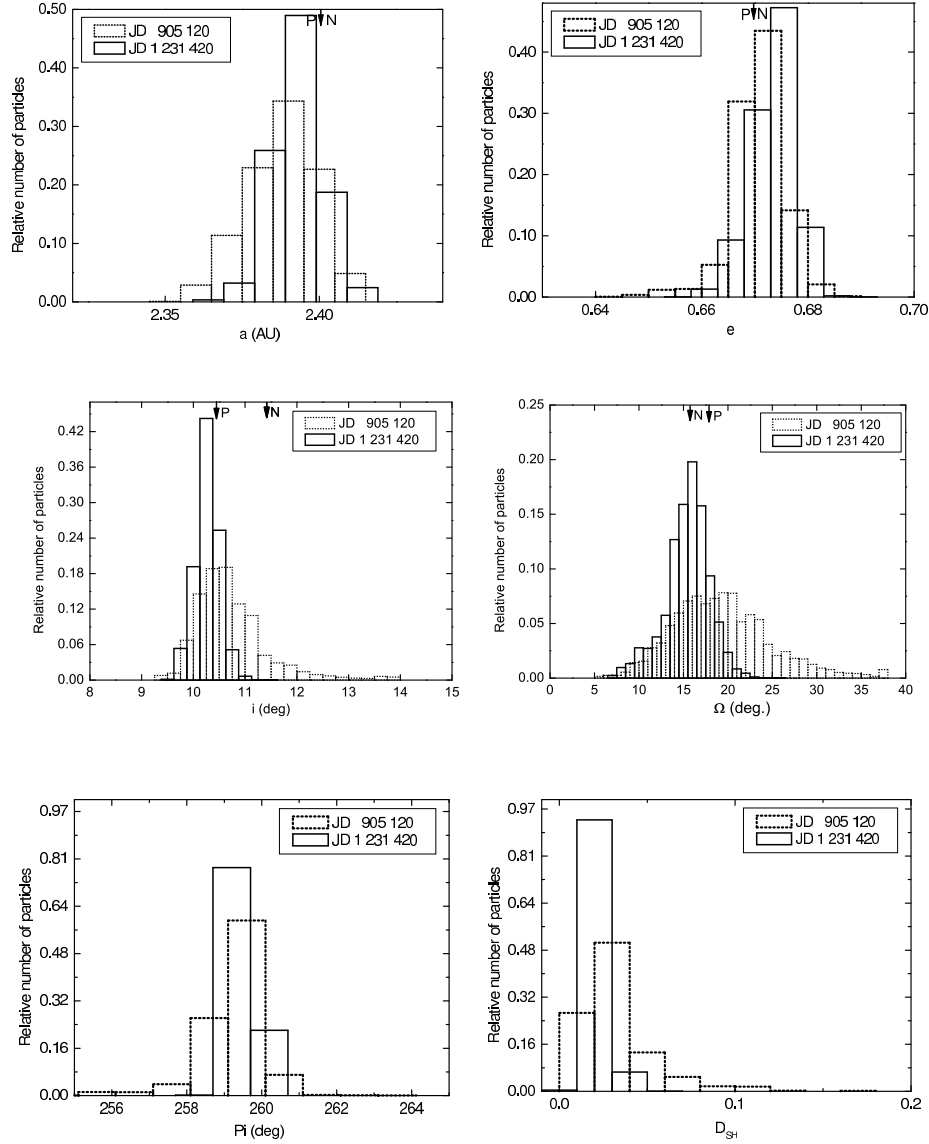
Figure 4. Histograms of orbital elements a, e, i, Ω, π and the D-criterion of modeled particles that left the parent body in the events $JD = 905\,120$ and $JD = 1\,231\,420$. ↓P and ↓N display the actual value of orbital element of Příbram and Neuschwanstein.
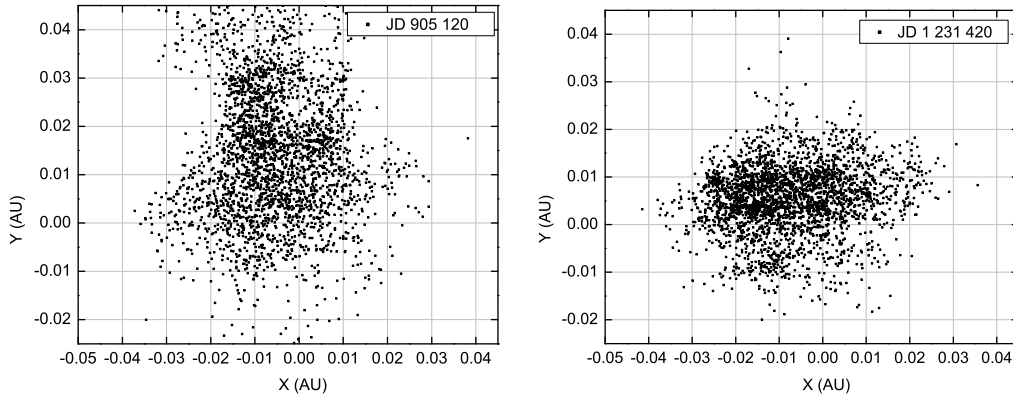

Figure 5. The cross-section of the target plain at the Earth with hits by the model particles after they complete one revolution around the Sun. Left - particles released in $JD = 905\,120$, right - particles released in $JD = 1\,231\,420$. The position (0,0) represents the Earth.
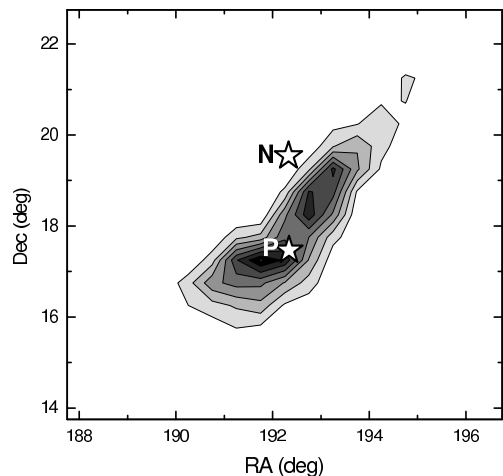
Figure 6. Radiants of modeled meteors in 2009 (eq. 2000.0). Contour plot shows a theoretical radiant probability density distribution if particles were released in the older event. Radiants of Příbram and Neuschwanstein are marked.

$$M = - \int_{0.01}^{30} 2.8 B D^{-3.8} m(D, \varrho) dD \; , \qquad (3)$$

where $m(D, \varrho)$ represents the mass of each pebble with the diameter D and the density ϱ.

Since the total mass and macroporosity (40 %) for Itokawa are known (Abe et al. 2006b), the density of the particles on the Itokawa is approx. $\varrho = 3,25\,g\,cm^{-3}$. Also the absorption spectrum of Itokawa in the near-infrared channel shows features similar to the LL5 or LL6 chondrite spectra (Abe et al. 2006a), with very similar densities $3.29 \pm 0.17\,g\,cm^{-3}$ (Wilkison & Robinson 2000). Generally, Itokawa-like body might be a progenitor of Příbram- and Neuschwanstein-like meteorites.

The constant B is then simply derived from equation (3) and the total number of all particles within the size range is calculated according to equation (2). The main idea is that the total mass of the asteroid will be disrupted to the boulders according to the mentioned size distribution. That is why the parent body must be a weakly bound rubble-pile asteroid. The equation (2) leads to about 4×10^{6} particles larger than $D \geqslant 0.6$ m or 3.8×10^{11} particles larger than $D \geqslant 1$ cm bound in the entire volume of the asteroid.

If we spread the total number of particles with the same size distribution along the orbit of the putative parent body, we can estimate the activity of the shower, for instance for one-centimeter particles and larger, as shown in Figure 7. The y axis on the left gives the individual inflow of particles onto the entire Earth in the one-day interval, the right y axis gives the biased activity for the one observing site (Central European conditions, e.g. at the Astronomical and Geophysical Observatory Modra with the all-sky video system, Tóth et al. 2008). The observing site counts were biased due to the burning height of the meteors over the surface (70 km), the fraction of observed time (night/day ratio in April, the month of Příbram and Neuschwanstein falls and proposed activity of the putative shower) and the weather conditions on the observing site (long term meteorological observations at AGO give 50% chance for observing at night).
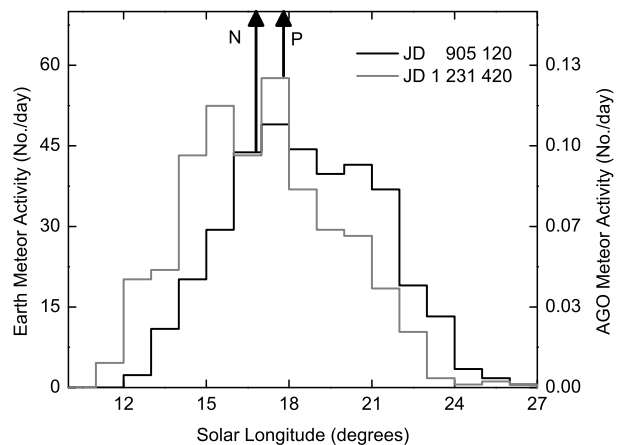

Figure 7. The activity of the potential meteor shower coming from the putative Příbram meteorite progenitor. The left y axis gives the number of particles that hit the Earth in the one-day interval, the right y axis gives the number of meteors observed from the AGO Modra site including biased observation due to bad weather, visible meteoric area, night/day ratio.
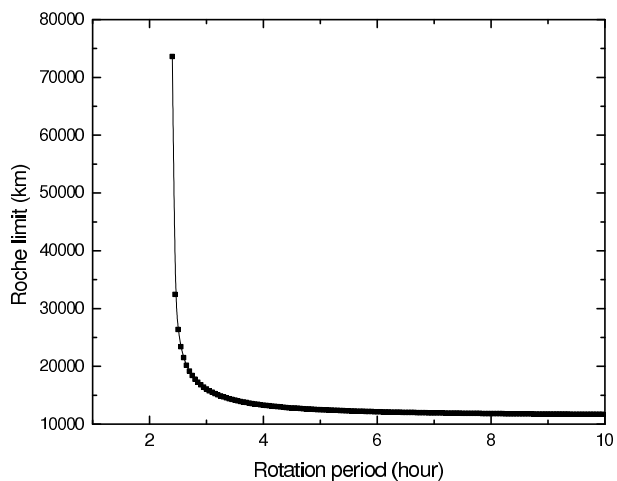

Figure 8. The Roche limit of tidal disruption as a function of asteroid rotation period close to spin barrier.

4   FREQUENCY OF THE NEA BREAK-UP BY EARTH TIDES

In this section we estimate the frequency of tidal disruption of close approaching NEAs to the Earth. Considering a rubble-pile structure of NEAs larger than ~ 200 meters, the frequency of such close approaches within the Roche limit of the Earth ($\sim 2R_{\oplus}$ for a non rotating body) is one per 11 000 years based on the impact frequency of NEAs (Brown et al. 2002).

Moreover, considering the rotation of the asteroid, the centrifugal acceleration on the asteroid's equator shifts the Roche limit of tidal break up farther from the Earth. The centrifugal acceleration due to the motion of the asteroid around the Earth (hyperbolic trajectory) was neglected. The function of the Roche limit depending on the asteroid rotation period is derived from the condition for the gravitational, centrifugal and tidal acceleration affecting the particle on the surface of the asteroid $a_g = a_\omega + a_{tid}$:
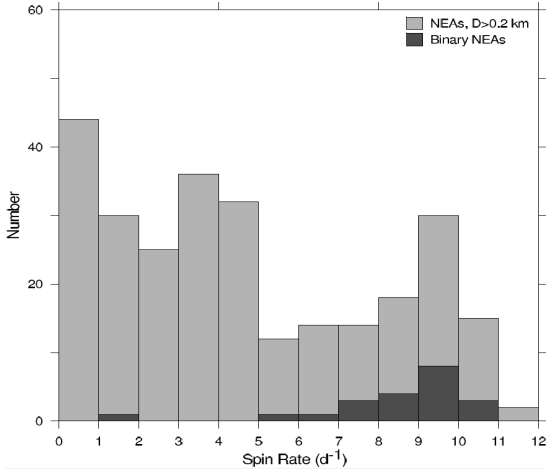
Figure 9. Distribution of spin rate of NEAs larger than 200 m (Pravec et al. 2008). Spin barrier is around 11 periods per day.

$$R_{Roche} = \sqrt[3]{\frac{GM_\oplus}{2\pi(\frac{G\rho}{3} - \frac{\pi}{P^2})}} \ , \qquad (4)$$

where R_{Roche} - the Roche limit depending on the spin ratio, G - gravity constant, $M_\oplus$ - mass of the Earth, ρ - bulk density of rubble pile NEA ($1900\,\mathrm{kg\,m^{-3}}$, same as Itokawa) and P is an asteroid principal axis rotation period. The function is depicted in Figure 8.

Therefore, the increase of the Roche limit due to asteroidal rotation changes the frequency of tidal disruption of NEAs in a close vicinity of the Earth. The frequency of Earth impacts (Richardson, Bottke & Love 1998) is given as

$$F_{imp} = P_{intr}N_D\pi R_\oplus^2 \ (1 + \frac{v_{esc}^2(R_\oplus)}{v_\infty^2}) \ , \qquad (5)$$

where P_{intr} is the intrinsic collisional probability of Earth-crossing asteroids (ECAs) with the Earth, N_D is a cumulative number of ECAs larger than D (in our case 200 m), $R_\oplus$ is the Earth radius (Richardson, Bottke & Love 1998). The part enclosed in the parentheses expands the impact area due to the Earth gravitational attraction.

The equation (5) is used for the estimation of the frequency of the tidal breakups considering the rotation of the asteroid. According to the spin rate distribution of NEAs larger than 200 m (Pravec et al. 2008, Figure 9 in this paper), there are 28% of bodies rotating in the range of spin rate 6 - 11 per day, near the spin barrier ~ 2.2 h. The Roche limit is substantially larger within this spin rate interval. Assuming the impact frequency on the Earth (Brown et al. 2002; Werner et al. 2002), we obtain a total frequency of close approaches within the Roche limit as a function of asteroid rotation. For each bin of the histogram in Figure 9, we can derive the equation similar to (5) with the corresponding Roche limit (4). Then the sum in the equation (6) means the total frequency of the NEA occurrence within the extended impact target. It is calculated from each interval i of the spin rate distribution.

The ratio of tidal disruptions in close vicinity of the Earth F_{tid} to impact frequency of NEAs on the Earth F_{imp} as follows:

$$\frac{F_{tid}}{F_{imp}} = \frac{\sum_i P_{intr}N_{D(i)}\pi R_{Roche(i)}^2 \ (1 + \frac{v_{esc(i)}^2 (R_{Roche(i)})}{v_\infty^2})}{P_{intr}N_D\pi R_\oplus^2 \ (1 + \frac{v_{esc,\oplus}^2 (R_\oplus)}{v_\infty^2})} \ , \ (6)$$

where $N_{D(i)} = N_D.w_i$ and w_i is a fraction of NEAs with given rotation period in i-th interval (Figure 9).

Using above calculation, the total frequency of tidal disruption of NEAs is seven times higher compared to the impact frequency of the entire NEA population larger than 200 m. For the specific impact frequency of 200 m NEAs equal to 2.3×10^{-5} per year on the Earth (Ivanov 2006), the tidal disruption frequency would be 1.6×10^{-4} per year. It means about once per 6 200 years.

5 TIDAL DISRUPTION AS THE SOURCE OF ASTEROIDAL METEOROIDS

The size-frequency distribution of near-Earth population originated by many complicated processes. It is generally accepted that the population of NEA is not primordial and it has come from other sources, mostly from the Main belt. The mean lifetime of objects on NEA orbits is also relatively short when compared with the lifetime of the Solar system (Bottke et al. 2002). Also the size distribution of the current NEA population might not copy the distribution of the Main belt progenitor population, mostly because several effects could change specific parts of population by a different rate (e.g. Yarkovsky effect, collisions between asteroids, etc.). Currently, models of the NEA population distributions are developed according to debiased observational data from telescopic surveys, crater counts on the Moon, from evolution models of the NEA population and impact frequency onto the Earth derived from annual large bolide influx. The tidal disruption of weak-bound asteroids flying-by planets inside the Roche limit could, therefore, enhance the population of NEAs of smaller diameters and deplete the population of larger bodies.

The mean lifetime of the asteroid in the NEA space depends on its evolutional path, and if considering only sources of asteroidal objects, the total mean lifetime is about 4×10^6 years (Bottke et al. 2002). During that time, until the object is swept away from the NEA space, certain fraction of objects of certain diameters has a chance to fly by the planet within the Roche limit and to be disrupted. Nevertheless, the disruption outcome depends on several parameters: the encounter velocity, asteroid shape, spin axis orientation and spin rate. We set the lower and upper limits for the size of objects incoming inside the Roche limit. The lower limit is given by the fact that objects 200 m and larger are not observed having the rotation faster than the spin barrier, which suggests their rubble-pile structures (Pravec & Harris 2000). To set the upper limit of disrupted NEA in the mentioned size range, we adopted the Stuart & Binzel (2004) cumulative size distribution for the NEA population. The model was altered according to the impact frequency that shows the size distribution of objects below 2 km has shallower slope (-1.7, Ivanov 2006):

$$\begin{aligned} N(> D) &= BD^{-1.7}; D \subset \langle 200\,m; 2\,km) \\ N(> D) &= BD^{-2.3}; D \subset \langle 2\,km; 6.6\,km) \end{aligned} \qquad (7)$$

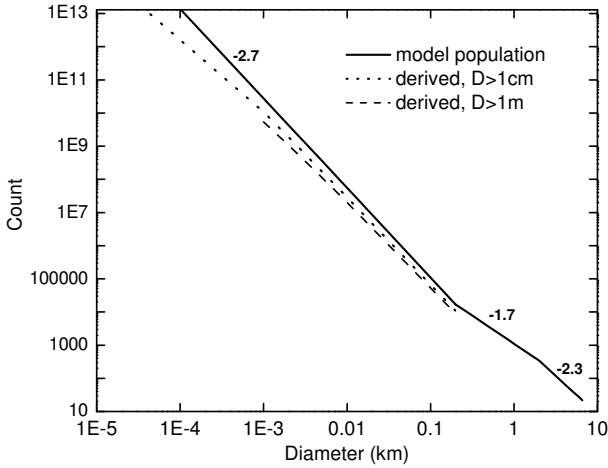Considering the steady-state population of NEA, where de-

Figure 10. Cumulative size distribution of the NEA population according to Werner et al. (2002) with the slopes -2.3 and -1.7 and by Brown et al. (2002) with the slope -2.7. The dotted curve represents the population without the contribution of the tidal disrupted matter if resulting particles of disruptions are larger than 1 m (slope -2.45), the dashed curve for particles larger than 1 cm (slope of the population -2.55).

pleted objects are replenished from outer sources, we get the upper limit for the asteroid size of 6.6 km. Such an object encounters the Earth below the Roche limit at most once during its lifetime in the NEA space (4×10^6).

We have found that at most $4.2 \pm 0.5\%$ of the NEA population undergoes tidal disruption due to Earth encounter within its lifetime assuming that each body that flies by the Earth within the Roche limit will be disrupted since it is possible that some fraction of the disrupted matter could be reaccumulated (Richardson, Bottke & Love 1998). The total mass loss in the size range from 200 m to 6.6 km per 4×10^6 years is approx. $10^{15} \, kg$. If we assume that all this mass is redistributed in a new cumulative size distribution with the slope equal to -2.8 (the slope of boulders and pebbles on Itokawa) within the size range from 1 cm to 200 m then the primordial slope of the population of NEA smaller than 200 m will be enhanced with the steeper population coming from the tidal disruption. There are several estimates of NEA population size distribution within the meteoroid sizes (1 cm-200 m), e.g. Ivanov (2006) and Brown et al. (2002). If we adopt the model derived from the bolide counts with the slope equal to -2.7 (Brown et al. 2002) and subtract the derived population from the tidal disruption, we reveal the size distribution of the NEA population as it would look like without the contribution from the tidal disintegration from the Earth. With respect to how finely the matter will be disrupted (down to 1 cm or 1 m), the resulting slope of the primordial population created by all effects, but not by tidal disruption, would be -2.55 or -2.45. It seems that the tidal disruption of the larger rubble-pile asteroids may change the size distribution slope of the population coming to the NEA region and makes it steeper.

6 CONCLUSION

This work concerns about the dynamical evolution and the activity of the theoretical stream of meteoroids that originated by the tidal disruption of the rubble-pile-like parent asteroid that we assumed moved in the orbit of the Příbram meteorite. The disruption of the asteroid and creation of the stream emerged when the node of the parent body got close to or crossed the Earth orbit. In the last 5000 years, the orbit of Příbram has fulfilled this condition twice: 4200 and 3300 years ago. In both events, the release of particles from the parent surface was modeled, and their following orbital evolution until the current date was traced. It takes several hundred years to spread particles around the entire orbit of the parent asteroid.

We assumed that the parent asteroid was similar to the Itokawa the complete disintegration of which would deliberate 3.8×10^{11} meteoroid particles with diameters larger than $D \geqslant 1 \, \text{cm}$. The activity of the proposed meteor shower observable in April is low according to Figure 7. Annual observation campaigns are needed in the first two weeks of April to detect any meteors coming from the proposed source.

The reverse approach to the problem might reveal what size and what amount of the matter coming from the tidal disruption of the asteroid were needed to create events like the Příbram and Neuschwanstein meteorite falls. If the average period between two falls of meteorites is 43 years (as in the case of the meteorites mentioned above), according to equation (2), such a stream of meteoroids must contain 2.2×10^7 - 1.0×10^{10} boulders of 0.6 m diameter, which was expected pre-atmospheric diameters of the meteorites (ReVelle, Brown & Spurný 2004). This number is in a good agreement with the previous work (Spurný, Oberst & Heinlein 2003). The parent body diameter can be estimated to be 0.6 - 5 km according to equation (3).

We have also estimated that the tidal disruption of rubble-pile asteroids by the Earth tides might populate the NEA space with smaller and compact meteoroids and, therefore, change the size distribution with lifting its slope.

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